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Effects of large-scale PV self-consumption on the aggregated consumption

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Abstract

Self-consumption is modifying the classical structure of the electrical grids worldwide. This energy supply method allows a distributed energy generation and the possibility of involving citizens in the electrical grid. Many countries have defined or are defining rules regarding self-consumption because of the evidence of its unstoppable growth. From the technical point of view, there are numerous associated advantages to the self-consumption, nevertheless it represents a new challenge in the management and design of the electrical grids. In general, the main generation technology for self-consumption is the PV energy. The PV generators are installed in a facility and their generation can be considered as a reduction on the local consumption or even negative consumption. Therefore, high penetration of PV self-consumption will modify the aggregated consumption shape of the electrical grid. The electrical grid should be able to respond to this new shape by adapting generation, controlling consumption or using storage systems. In this paper, we analyze the effects of high penetration of PV self-consumption on the aggregated consumption of the Spanish electrical grid. For this analysis we use historical solar resource data from different cities of Spain and historical data of the aggregated consumption of the country. The results show that PV self-consumption can smooth the aggregated consumption shape, mainly during summer periods. On the other hand, the PV self-consumption can increase the variability of the aggregated consumption shape for high penetration levels.

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Keywords: Self-consumption, PV systems, electrical grid, aggregated consumption

1. Introduction

Self-consumption of PV energy is a key factor for the renewal of electrical grids, from a generation based on fossil fuels to renewable energy sources. This change is not only limited to the generation technology but to the structure of the electrical system too, from a centralized model to a distributed one. Many countries are promoting the PV self-consumption and they are moving towards self-consumption schemes to boost the growth of the renewable energy[1].

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From the economics point of view, the self-consumption has the advantage of competing with retail prices rather than wholesale prices. This fact makes the self-consumption already profitable in many countries, even in the absence of regulatory subsidies [1,2]. Therefore, it is an active research field [3].

Most previous works are focused on the self-consumption analysis and enhancement from a local perspective: how a PV generator affects the local energy balances or how the amount of self-consumed energy can be increased. These works usually combine the PV generation with energy storage and load management, the latter commonly known as Demand Side Management (DSM) [4,5]. From the energy storage point of view, this can be used to store the excess of PV generation to be used at non generation hours, mainly during the evening consumption peaks [6]. On the other hand, DSM is usually focused on the load shifting by displacing the consumption from the non generation hours to the generation ones. This load shifting increases the use of the local PV energy without the expenses associated to the use of an storage system [7].

Although the maximization of the self-consumption entails a reduction of the energy exchange with the electrical grid, this reduction does not always occur in power. The use of a renewable source involves that a local facility will have generation and consumption peaks. These peaks should be handled by the electrical grid. This issue takes relevance as the PV penetration increases, a fact that is expected in the coming years [1]. Currently, there is an increasing number of works that address the integration of PV self-consumption with the electrical grid. For example, the study of the effects on the distribution networks is receiving increasing attention [8,9]. The integration of large amounts of PV generation brings new challenges for the design and maintenance of these networks [10]. As in the local case, the energy storage and DSM are used to improve the integration of PV self-consumption with the electrical grid. They are usually combined with artificial intelligence techniques and framed in the smart grid concept [11]. In order to incentive the users to participate in this integration, policies and tariffs play a key role [12,13].

In this paper, we analyze the effects of the PV self-consumption on the aggregated consumption of an electrical grid, particularly in the Spanish electrical grid. This analysis only takes into account the effects of the local PV generators without considering the use of storage systems or DSM. The remainder of this paper is as follows: The simulated electrical grid, the PV generation profiles and the assessment method are explained in Section 2. The performed simulations and their results are shown in Section 3. Finally, Section 4 concludes the paper.

2. Description of the studied electrical grid

In this section, we define the simulated electrical grid and the assessment factors. The goal of the analysis presented in this paper is to show the effects of high penetration of PV self-consumption on the aggregated consumption shape of the Spanish electrical grid. This analysis has been done by using real consumption and meteorological measurements. On the consumption side, we use the peninsular Spanish aggregated consumption during 2013 with an annual consumption around 246 TWh. This consumption was measured by the Spanish grid operator *Red Eléctrica de España* with a sampling period of 1 hour. In order to simulate the national generation, the PV generation profiles have been calculated for six different cities of Spain: Caceres, Ciudad Real, Logroño, Madrid, Santiago and Soria. This calculation of the PV generation profiles has been done by using the real irradiance and temperature data from these cities during 2013. These data has been translated to AC power by using the model of a typical PV facility [14]. The combination of these cities allows to simulate the national PV generation considering the different climate regions. Fig. 1 shows a map with the studied cities and the different climate regions. Each zone in the map represents a climate region, these zones are defined by the irradiance, where yellow represents a low irradiance and dark red represents a high irradiance. At least one city for each zone has been chosen. Santiago corresponds to the zone 1, Logroño corresponds to the zone 2, Soria corresponds to the zone 3, Ciudad Real corresponds to the zone 4, Caceres corresponds to the zone 5, and Madrid as the capital, in the zone 4 has also been included. In order to represent the penetration of PV generation in the electrical grid, the *PV penetration factor* ρ^{PV} is defined as the percentage of energy generated by the PV generation sources regarding the total consumed energy. For example, $\rho^{PV} = 50\%$ implies that the annual generated PV energy is 123 TWh.

The electrical grid has been represented in six different nodes where each node has one of the aforementioned PV generation profile. The maximum nominal PV power generation in each node is 24 GW, such that the total power generation of all nodes is 144 GW. This generation power corresponds to a yearly energy generation around 246 TWh, which is the same energy amount than the yearly peninsular energy consumption of Spain. This amount is chosen

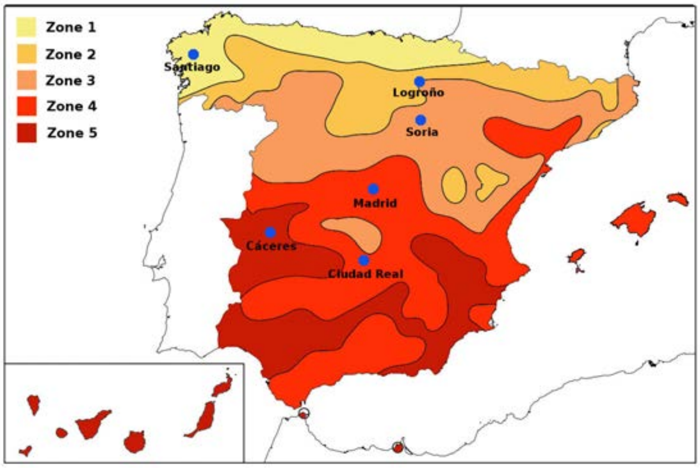


Fig. 1. Climate zones of Spain, where the chosen cities for this analysis have been marked with blue dots.

to analyze the effects of high levels of PV penetration on the grid. The same procedure has been followed for the consumption. The aggregated consumption of Spain has been divided over the six nodes. In this case, there are not differences on the shape of the aggregated consumption, considering a similar consumption profile throughout the country. This permits to analyze the capacity of PV penetration in all regions, introducing each PV generation to the same consumption profile. Energy losses or side effects are not taken into account, hence this study is limited to balances of consumption.

The PV generation of each node is assumed as self-consumption. The self-consumption is considered as a negative consumption, e.g., if a node has a generation of 1 kW, it is consuming -1 kW. This consideration allows introducing the self-consumption in the aggregated consumption and to observe its effects. As a final appreciation, the aggregated consumption is always positive. It means that if the PV generation is greater than the whole consumption of the grid, the aggregated consumption will be zero instead of taking negative values. Because the aim is to analyze the effects of the local PV generators without considering the use of storage systems or international exchanges, the excess generation has not been taken into account.

2.1. Assessment factors

The assessment factor used in the local framework is the *self-consumption factor*, denoted by ξ[7]. It represents the fraction of the electrical energy consumed by the loads which is only supplied by the local generation sources. The following equation defines mathematically the self-consumption factor:

$$\xi = \frac{E_{PV,L}}{E_L} \tag{1}$$

where $E_{PV,L}$ is the energy directly supplied by the PV generator to the loads and E_L is the energy consumed by the loads. Also, as expected by its own definition, the range of ξ is $[0, 1]$, because this factor is normalized by the total consumption of the local facility. This normalization also allows comparing the operation of different facilities regardless of their sizes. $\xi = 0$ would be the case of a facility with no local generation available, whereas, $\xi = 1$ means that all energy is locally supplied, for instance, a facility isolated from the electrical grid. The assessment factor used to analyze the variability of the aggregated consumption is the *Crest Factor*, denoted by C. It is a measure of a waveform, showing the ratio of peak values to the average value, such that:

$$C = \frac{|x|^{peak}}{x^{rms}} \quad where \;\; x^{rms} = \sqrt{\frac{x_1^2 + x_2^2 + \ldots + x_N^2}{N}} \tag{2}$$

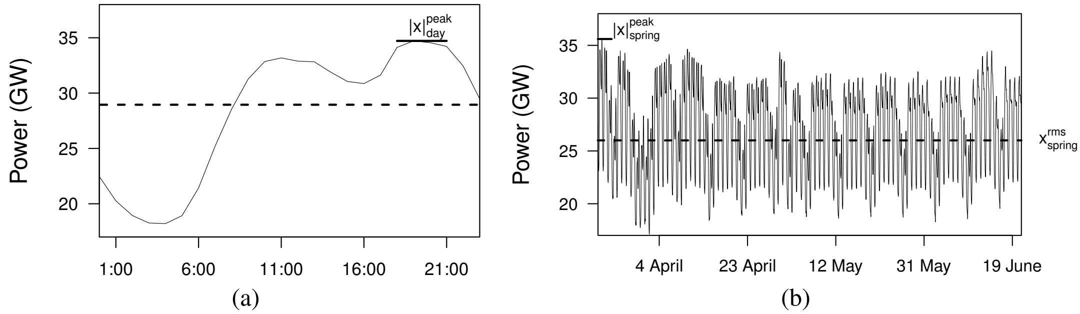


Fig. 2. Example of the crest factor for two different periods of the aggregated consumption: a) crest factor of a day $C_{day} = 1.19$ and b) crest factor of a season (spring) $C_{spring} = 1.36$.

where N is the number of samples taken from the aggregated consumption, $|x|^{peak}$ is the absolute value of the maximum peak and x^{rms} is the root mean square. The crest factor makes reference to a concrete time interval in which the aggregated consumption is evaluated.This time interval is denoted with a subscript, for example, the crest factor of a day is denoted by C_{day}. Figure 2 shows an example of the crest factor for a day and a season (spring) of the aggregated consumption. In the analysis done in this paper, C_{year}, C_{season} and C_{day} have been calculated. The daily crest factors of the simulated grid have been averaged, so that:

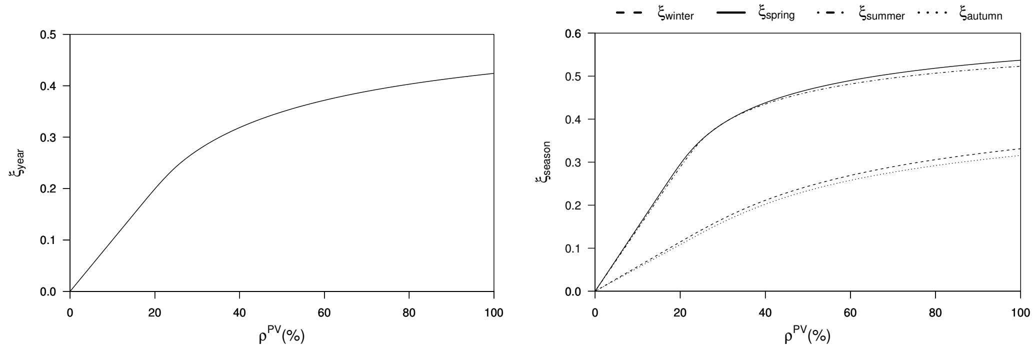
$$\bar{C}_{day} = \frac{1}{N}\sum_{i=1}^{N} C^{i}_{day} \tag{3}$$

where N denotes the number of days of the assessed period. For example, $\bar{C}_{day}$ for spring is the average of C_{day} of the 92 days of this season. In the same way, $\bar{C}_{day}$ for one year is the average of C_{day} of the 365 days of the year.

3. Simulation results

We conducted the simulations of the electrical grid by using *GridSim*. *GridSim* is an open source simulator developed to analyze the power balances on a virtual smart grid. A campaign of experiments has been performed to study how the PV penetration affects the self-consumption and the aggregated consumption shape. An experiment consists of simulating the electrical grid during one year or one season for a concrete ρ^{PV} value. The simulation step is 1 min. The real measurements have been interpolated in order to use the real aggregated consumption with a sampling period of 1 min. Thus, the aggregated consumption is the result of adding all nodes consumption including the self-consumption. To analyze different levels of PV penetration, the value of the nominal PV power generation is incremented for each experiment, from zero to the maximum. During each experiment the self-consumption factor and the crest factors are calculated.

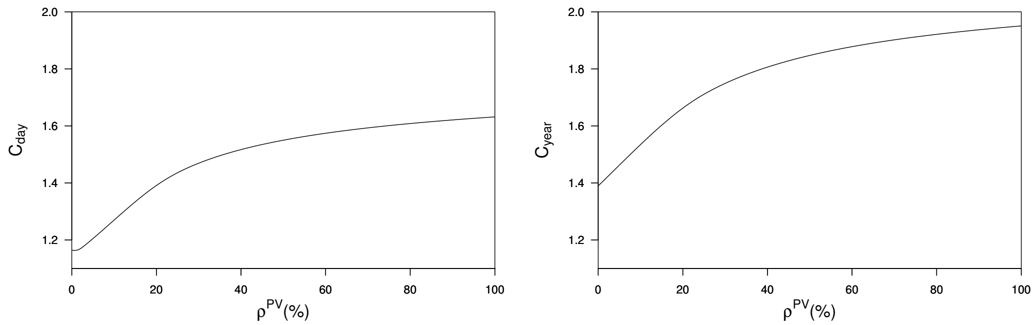
Fig. 3a shows the development of the self-consumption factor for different percentages of ρ^{PV} in the electrical grid. The self-consumption factor has a positive trend regarding ρ^{PV}: the higher the ρ^{PV}, the higher the self-consumption factor. However, for $\rho^{PV} > 35\%$ the self-consumption factor has a lower slope. This effect is caused by the generation excess at midday: the PV generators supply all consumption during some hours of some days of the year. Although more PV energy is generated in those hours, the consumption has already been supplied, and the energy remainder is dismissed in this study. In addition, this relationship varies for the different seasons for both the solar resource and the aggregated consumption shape. Fig. 3b shows the development of the self-consumption factor for all seasons. The self-consumption is considerably higher during summer and spring than in autumn and winter, reaching differences close to 30%. Notice that main consumption peaks in summer and part of spring take place during midday in Spain. This correlation between consumption and generation entails a high growth of the self-consumption factor for $\rho^{PV} < 35\%$. For $\rho^{PV} > 35\%$, the reduction of the slope of the self-consumption factor is more pronounced in summer and spring. This effect has the same causes than in the annual case: the PV generation excess reduces the local



(a) (b)

Fig. 3. Development of the self-consumption factor for different percentages of ρ^{PV} a) during one year and b) for every season.

consumption to zero at certain times. From these results it follows that there is a strong deformation of the aggregated consumption shape.

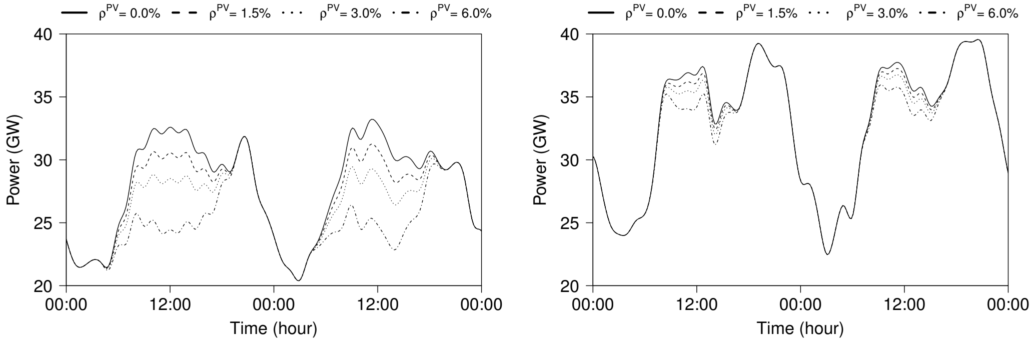


(a) (b)

Fig. 4. Development of the crest factors for different percentages of PV penetration factor ρ^{PV}, in a time interval of a year: a) $\bar{C}_{day}$ and b) C_{year}.

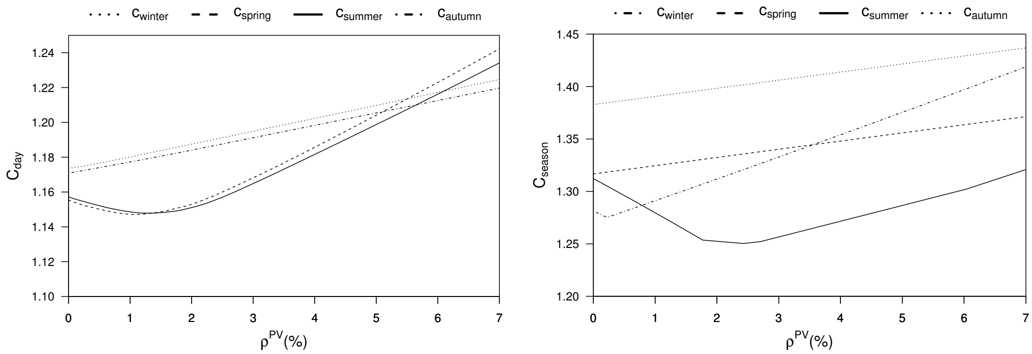
Fig. 4 shows the development of the crest factors for different percentages of ρ^{PV} in the electrical grid. This factor has been applied to different time intervals, where the maximum peak is divided by the root mean square of the aggregated consumption during the studied interval: C_{year} and $\bar{C}_{day}$. In general, the crest factors increase with ρ^{PV}, but this relationship is not linear. For $\rho^{PV} > 35\%$, the slope of the crest factors decreases as in the self-consumption factor case. This effect is also caused by the generation excess: the consumption is reduced to zero and the generation increment does not modify the root mean square of the aggregated consumption. However, for $\rho^{PV} < 3\%$, C_{day} decreases. This implies that for low PV penetration levels the difference between the peak and the root mean square is reduced by the presence of PV self-consumption. Thus, a low PV penetration helps to flatten the aggregated consumption curve by minimizing the maximum peak. This reduction is caused by the correlation between consumption and PV generation during summer and spring in Spain. Fig. 5 shows an example of this effect. The maximum PV generation is at midday together with the maximum consumption peaks during summer days—see Fig. 5a. On the other hand, the maximum consumption peaks during winter days take place at evening, which cannot be reduced by the PV generation—see Fig. 5b.

The daily and seasonal crest factors have been calculated for $\rho^{PV} < 7\%$ to analyze the crest factor decrease. Fig. 6 shows the seasonal crest factors for $\rho^{PV} \leq 7\%$ that corresponds to 10 GW of PV power generation. for a greater ρ^{PV} the crest factors increase for all cases. During spring and summer, the crest factors decrease for certain values of ρ^{PV}. $\bar{C}_{day}$ decreases around 1% for $\rho^{PV} \approx 1\%$ that corresponds to 1.4 GW of PV power generation—see Fig. 6a. From this



(a) (b)

Fig. 5. Example of the aggregated consumption for different PV penetrations: a) during two summer days and b) during two winter days.



(a) (b)

Fig. 6. Development of the crest factors for $\rho^{PV} \leq 7\%$, for every season, where: a) $\bar{C}_{day}$ and b) C_{season}.

value, $\bar{C}_{day}$ increases for all seasons. This implies that the increment of PV generation reduces the root mean square of the aggregated consumption without reducing the daily peaks. These effects are slightly different for C_{season}—see Fig. 6b. During winter and autumn, an increment of PV penetration of 7% causes an increment of the seasonal crest factors around 3%. During spring, the crest factor increases around 14%, always remaining below the winter crest factor. There is an initial decrement of C_{spring} which is almost negligible. On the other hand, during summer, the crest factor maintain the same value for 10 GW of PV power generation. The summer crest factor even decreases around 4% for $\rho^{PV} = 2.5\%$ that correspond to 3.6 GW of PV power generation. Differences in trends of both types of crest factors are caused by the ability of the PV self-consumption to affect the consumption peaks. For example, during summer the generation reduces the maximum peaks at midday until they reach the same level than the evening peak. In this case, the seasonal crest factor is reduced. From that moment, the PV generation reduces the root mean square of the aggregated consumption but does not modify the consumption peak. In this case, the seasonal crest factor is increased. For the daily crest factor, this effect only happens during certain days. $\bar{C}_{day}$ is an average and it is affected by days where this effect does not happen.

This reduction of the crest factor may also imply a reduction in the difference between peaks (highest consumption) and valleys (lowest consumption) of the aggregated consumption. We define the difference between peak an valley of the day i as $\Delta_i = max(P_i(t)) - min(P_i(t))$, where $P_i(t)$ is the aggregated consumption of the day i. Fig. 7 shows the development of the daily differences between peaks and valleys for $\rho^{PV} \leq 7\%$ divided into the four seasons. This figure is composed by a strip which is limited by the maximum and minimum of Δ_i for the corresponding season. It implies that the difference between the peak and the valley of any day of the season is always in this strip. In general,

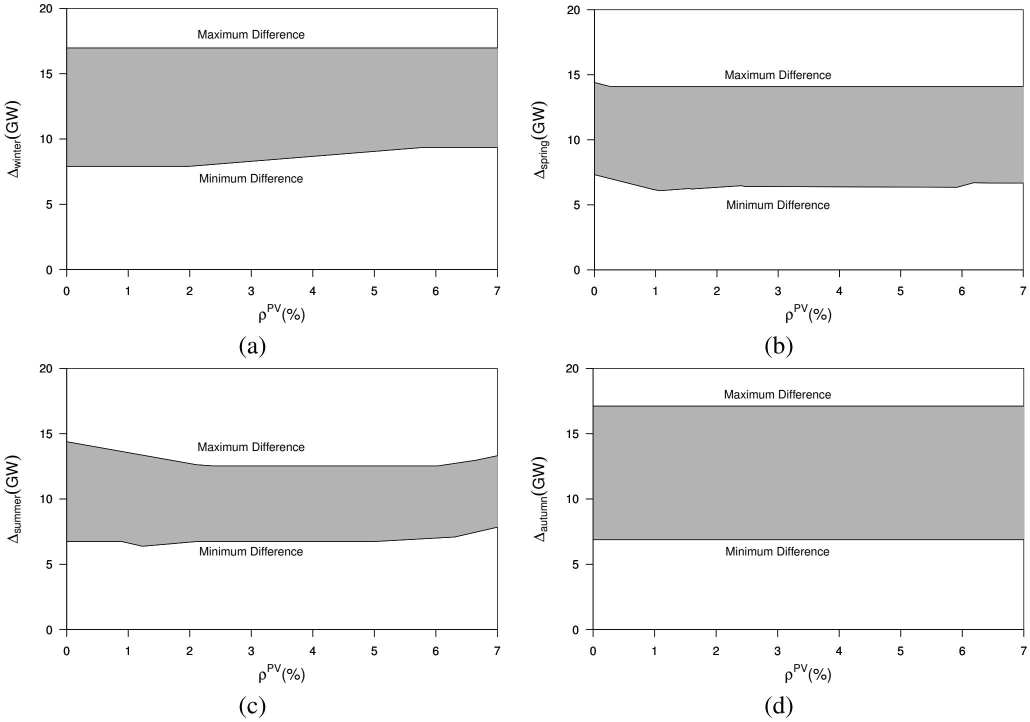


Fig. 7. Maximum and minimum daily difference between valleys and peaks for different percentages of ρ^{PV} for each season, where: a) winter, b) spring, c) summer and d) autumn.

there is not an increment of the maximum of the differences between peaks and valleys because of the presence of PV self-consumption. Notice that the maximum of these differences can be considered the worst case from the electrical grid stability point of view. On the other hand, during summer, the maximum is reduced in 2 GW because of the use of 3.6 GW to 8.6 GW of PV power generation—see Fig. 7c. Even in spring, a slight reduction of the maximum can be appreciated, around 0.5 GW—see Fig. 7b. These results imply that for $\rho^{PV} \leq 7\%$ the PV self-consumption always reduces the differences between peaks and valleys.

4. Conclusions

This paper analyzes the effects of high penetration of PV self-consumption on the aggregated consumption of the Spanish electrical grid. For this purpose, real measurements of the Spanish aggregated consumption and meteorological measurements of 2013 have been used. The simulated electrical grid has been divided in six nodes to consider different climate regions. The PV generation profiles have been calculated for six cities, at least one city for each of the climate regions. The self-consumption factor and crest factor have been used as assessment factors.

The self-consumption factor represents the capacity of PV generation to supply the loads. The results show that this factor has a positive trend regarding the PV penetration. This is considerably higher during summer and spring, reaching values close to 50%, for a yearly PV penetration around 35%. This happens because the main consumption peaks in summer and spring take place during midday in Spain. On the other hand, the self-consumption factor has a lower slope for high values of PV penetration. This implies that part of the generated energy is not consumed.

To analyze the variability of the aggregated consumption, the crest factor was used by showing the ratio of peak values to the average value. This factor has been calculated for different percentages of PV penetration for different time intervals: days, seasons and year. In general, the crest factor increases with the PV penetration. However for low PV penetration values, the crest factor can decrease, mainly during summer periods. This reduction of the crest factor implies also a reduction in the difference between peak and valley of the aggregated consumption. The results show that the PV self-consumption reduces these differences for a PV generation installed lower than 10 GW in a self-consumption scheme. In particular, the maximum difference between peak and valley is reduced in 2 GW during summer and 0.5 GW during spring. The maximum differences are not modified during the rest of the year.

The reduction of the maximum differences between peaks and valleys implies a smoother aggregated consumption, making easier the management of the grid. Although there are still many technical challenges regarding to the PV distributed generation, mainly due to their intermittency[15], these results imply that for a low PV penetration, PV self-consumption may be used to boost grid stability.

This reduction in the variability of the aggregated consumption of the electrical grid has special relevance during summer periods because of the correlation between the PV generation and the consumption peaks. This effect has been observed in Spain because of its meteorological conditions where part of the country has low heating consumption and high air conditioning consumption. This study could be extended to other countries or regions with warm climates, where the use of the PV self-consumption can strengthen its advantages.

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